

# EXPERIMENTAL STUDY ON THE RESPONSE OF MISTUNED BLADED DISK

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To my beloved Father and Mother

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## ABSTRACT

Gas turbine vibrations can be caused by several mechanisms, but some blade failures cannot be explained by the more commonly known mechanisms and theories. These blades are conveniently regarded as rogue “mistuned” blades that had failed from abnormally high stresses. This led to extensive studies of bladed disk vibration characteristics. There are currently no theoretical predictions which can fully explain the blade vibration response in the presence of airflow due to the complicated aerodynamic structural interaction. A literature review is presented on mistuned blades research. This work involved the experimental study of forced response amplitude of model blades due to structural mistuning and inlet flow distortion in the presence of an air flow. This controlled study of blade mistuning with inlet flow distortion therefore represents a nearly realistic environment involving rotating blades in the presence of airflow. Previous work by others were usually based on a non-rotating blade. The presence of airflow which introduced effects of fluid structural interaction was not considered in previous works on mistuned blades. The primary intent of this work was to acquire the data while the blade is rotating in a situation that almost replicates the actual situation. A test rig was fabricated consisting of a rotating bladed assembly, an inlet flow section (where flow could be controlled or distorted in an incremental manner), flow conditioning module and an aerodynamic flow generator (air suction module with an intake fan) for investigations under laboratory conditions. Instrumentations included ultra-lightweight surface mounted pressure sensor on a rotating blade and vibration accelerometer on typical blades with signal routed through a telemetry system from the rotating shaft. These then allowed studies under a nearly realistic environment with rotating blades vibrations and pressure distributions measurements in the presence of airflow for the study of blade mistuning and inlet flow distortion with structural and aerodynamic interaction. Computational studies for vibration response of the blades and computational fluid dynamics of the inlet flow distortion were also undertaken to support the experimental studies. Tests were undertaken for a combination of different air-flow velocities and blade rotational speeds. The experimental results showed that the vibration responses of a mistuned blade (in a single stage of 12 bladed rotor assembly) were greatly influenced by the flow velocity, flow-induced frequency and blade/vane count. When the inlet flow was distorted, additional frequencies were excited and the amplitudes of these excited frequencies increased with increase in flow velocity.

## ABSTRAK

Getaran turbin gas boleh disebabkan oleh beberapa mekanism, tetapi terdapat sebahagian kegagalan bilah turbin yang tidak dapat diterangkan oleh mekanisma kegagalan dan tiori biasa. Bilah ini dianggap sebagai ‘bilah-bilah buruk talaan sepi’ (rogue mistuned blades) yang gagal disebabkan oleh ketegangan tinggi. Ini telah menyebabkan banyak kajian dijalankan oleh penyelidik ke atas ciri-ciri getaran disk bilah. Bagaimanapun, kini masih tiada ramalan tiori yang boleh menerang getaran bilah dalam aliran udara yang disebabkan oleh interaksi struktur aerodinamik yang rumit. Satu kajian literatur dalam bidang bilah talaan sepi (mistuned blades) diberi dalam tesis ini. Penyelidikan yang dijalankan ini melibatkan satu kajian makmal untuk sambutan getaran bilah-bilah model akibat daripada ‘talaan sepi’ (mistuning) struktur dan gangguan aliran masuk dalam satu aliran udara. Kajian oleh pihak lain biasanya melibatkan bilah yang tidak berputaran. Aliran udara memberi kesan interaksi bendalir struktur yang belum pernah dipertimbangkan dalam kajian bilah talaan sepi. Objektif utama kajian ini adalah untuk memperolehi data semasa bilah berputaran dalam satu keadaan yang mereplikakan keadaan yang sebenar. Sebuah pemasangan kajian dibina daripada pemasangan bilah yang berputaran, bahagian aliran udara masuk (yang boleh dikawal dan diganggu mengikut kadar terkawal), bahagian kawalan aliran dan penjana aliran aerodinamik (modul sedutan angin dengan kipas) untuk kajian makmal. Instrumentasi termasuk pengesan tekanan ultra-kecil yang dipasang di atas permukaan bilah dan pengesan getaran di atas bilah di mana isyarat-isyarat instrumentasi diperolehi melalui sistem telemetri yang dipasang di atas syaf. Ini mebolehkan kajian di bawah satu keadaan yang hampir sebenar di mana getaran bilah serta taburan tekanan bilah berputaran dikaji dalam aliran udara untuk kesan talaan sepi dan aliran masuk terganggu. Kajian berkomputer bagi sambutan getaran bilah dan kajian dinamik bendalir berkomputer (CFD) bagi gangguan aliran masuk dijalankan juga untuk menyokong kajian makmal. Ujikaji-ujikaji dijalankan untuk pelbagai kombinasi halaju putaran dan aliran angin yang berlainan. Keputusan ujikaji menunjukkan bahawa bilah yang bermasalah ‘talaan sepi’ (dalam satu pemasangan 12 bilah) mempunyai sambutan getaran yang dipengaruhi oleh kelajuan aliran angin, frekuensi paksaan aliran, dan bilangan kepingan bilah. Apabila berlakunya gangguan aliran masuk, lebih banyak frekuensi getaran terjana dan amplitudnya berubah dengan penambahan halaju aliran.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENTS	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xii
	LIST OF FIGURES	xiv
	LIST OF SYMBOLS	xxi
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Introduction	1
	1.2 Factors Affecting Blade Vibrations	2
	1.2.1 Self Excited Vibrations	2
	1.2.2 Forced Vibrations	3
	1.2.3 Aerodynamic Excitations of Turbomachinery	3
	1.3 Aeroelasticity of Turbine Blade	4
	1.4 Mistuning	5
	1.5 Inlet Flow Distortion	5
	1.6 Vibratory Stresses Prediction	7
	1.7 Fatigue Life Prediction of Turbomachine Blading	8
	1.8 Flow Defects	9
	1.9 Problem Definition	10
	1.10 Problem Formulation	11
		12

1.11	Significance of the Problems	12
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>15</b>
2.1	Introduction	15
2.2	Blade Response and Mistuning	15
2.3	Flow Induced Vibration	18
2.4	Aeroelasticity of Turbomachinery	19
2.5	Rotor-Stator Interaction	20
2.6	Fluid-Structure Interaction	20
2.7	Flutter in Turbomachinery	22
2.8	Aerodynamic Effect on Turbomachinery	23
2.9	Inlet Flow Distortion	25
2.10	Summary of the Past Works	26
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	<b>28</b>
3.1	Introduction	28
3.2	Problem Isolation	28
3.3	Concept for a Laboratory Study	29
3.3.1	Configuration	29
3.3.2	Method of Excitation	29
3.4	Improved Methods	30
3.5	Flow Distortion Investigation	30
3.6	Structure of the Study	30
<b>4</b>	<b>COMPUTATIONAL MODELING</b>	<b>32</b>
4.1	Introduction	32
4.2	Finite Elements Modeling of the Blade	33
4.2.1	Results of Finite Elements Modeling	35
4.3	Analytical Solutions	35
4.4	Experimental Modal Testing	36
4.5	Aeroelasticity Modeling	40
4.6	Computational Fluid Dynamic (CFD) Simulations	50

<b>5</b>	<b>TEST RIG DESIGN</b>	<b>53</b>
5.1	Introduction	53
5.2	Experimental Intent	54
5.3	Working Section	55
5.3.1	Bladed Disk	55
5.3.2	Shaft Design	56
5.3.3	Inlet Guide Vane	57
5.3.4	Driving Motor	57
5.4	Airflow Generation	58
5.5	Airflow Conditioning	59
5.6	Flexible Joint Design	60
5.7	Validation of the Test Rig	61
5.7.1	Structural Dynamic Responses	61
5.7.1.1	Natural Frequencies	62
5.7.2	Airflow Performance and Uniformity	65
5.7.3	Sensitivity Tests of Blades	65
<b>6</b>	<b>INSTRUMENTATIONS</b>	<b>71</b>
6.1	Introduction	71
6.2	Dynamic Response Measurement	71
6.3	Pressure Response	72
6.4	Slip Ring	73
6.5	Rotor Speed Control	74
6.6	Data Acquisition Box (DAQ)	75
<b>7</b>	<b>EXPERIMENTAL SET-UP AND TEST PROCEDURES</b>	<b>76</b>
7.1	Introduction	76
7.2	Experimental Set-Up	76
7.3	Tests Procedures	80
7.3.1	Field Performance Measurement of Fan System	80
7.3.2	Structural Mistuning	81
7.3.3	Non-Uniform Aerodynamic Loading on the Blade	81



<b>8</b>	<b>PERFORMANCE MEASUREMENT OF THE TEST RIG AIRFLOW</b>	<b>83</b>
8.1	Introduction	83
8.2	Importance of the Test	83
8.3	Test Procedures	84
	8.3.1 Traverse Locations	85
	8.3.2 Test Rig Airflow Performance Investigation Experiment	87
<b>9</b>	<b>EXPERIMENTAL RESULTS OF BLADE VIBRATION RESPONSE</b>	<b>93</b>
9.1	Introduction	93
9.2	Natural Frequencies and Corresponding Mode Shapes of the Blades	93
9.3	Centrifugal Effects on the Blades Frequency Responses	99
9.4	Blade and Inlet Vane Passing Frequencies	101
9.5	Responses for Standard Blade at Different Angular Positions	102
9.6	Vibrational Frequency Responses Results at Constant Airflow Speed	109
	9.6.1 Frequency Responses for the First Mode Vibration	109
	9.6.2 Frequency Responses for the Second Mode Vibration	115
	9.6.3 Frequency Responses for the Overall Vibration	119
<b>10</b>	<b>EXPERIMENTAL RESULTS OF PRESSURE RESPONSES ANALYSIS</b>	<b>124</b>
10.1	Vibrational Frequency Responses Analysis	124
10.2	Summary of the Results	139
	10.2.1 Structural Influence	139
	10.2.2 Aerodynamic Considerations	140

<b>11</b>	<b>THE EFFECT OF NON-UNIFORM AERODYNAMIC LOADING ON THE BLADE RESPONSES</b>	<b>142</b>
11.1	Introduction	142
11.2	Experimental Procedures	142
11.3	Results of Analysis and Conclusion	143
<b>12</b>	<b>DISCUSSION OF RESULTS</b>	<b>150</b>
12.1	Introduction	150
12.2	Summary of the Findings	150
12.3	Discussion of the Findings and Comparison with previous Works	152
<b>13</b>	<b>CONCLUSIONS AND RECOMMENDATIONS</b>	<b>155</b>
13.1	Concluding Remarks	155
13.2	Recommendations on Future Work	157
	<b>REFERENCES</b>	<b>158</b>
	<b>Appendices A-D</b>	<b>166 - 203</b>

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
4.1	Natural frequencies of the blade using three different methods	37
5.1	Natural frequencies for bearing A and B	63
5.2	Natural frequencies for working section	63
5.3	Measured natural frequencies (Hz) for the normal and mistuned blades	64
5.4	Running speeds of the rotor	64
5.5	Average and standard deviation of the normal blade natural frequency at different angular locations	70
7.1	Blades mistuning designations	77
7.2	Summery of test variables for fan performance	78
7.3	Summery of test variables for structural mistuning	78
7.4	Matrix of test conditions for fan performance	78
7.5	Matrix of Test Conditions for blade of structural Mistuning	79
7.6	Matrix of Test Conditions for each blade for blade configurations	79
7.7	Matrix of Test Conditions for blade non-uniform aerodynamic loading	80
8.1	Traverse Locations Formula	86
8.2	Measuring depth locations starting from the duct surface	87
9.1	Natural frequencies for the twelve normal blades	94
9.2	Blade first mode comparison of the experimental and FEM Results	96
9.3	Blade second mode comparison of the experimental and FEM results	96

9.4	Blade third mode comparison of the experimental and FEM results	97
9.5	1 <sup>st</sup> mode natural frequencies for tuned and mistuned blades adjusted for centrifugal stiffening effect (rotor speed 1500 rpm)	100
9.6	2 <sup>nd</sup> mode natural frequencies for tuned and mistuned blades adjusted for centrifugal stiffening effect (rotor speed 1500 rpm)	100
9.7	3 <sup>rd</sup> mode natural frequencies for tuned and mistuned blades adjusted for centrifugal stiffening effect (rotor speed 1500 rpm)	100
9.8	Blade and vane passing frequencies	102
9.9	Relative Blade/Vane passing frequencies	102
9.10	Normal blades responses at different angular locations	108

## LIST OF FIGURES

<b>FIGURE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
1.1	Fluid-structure Interaction	4
3.1	Flow Chart of the Research Strategy	31
4.1	Blade model using in Ansys	34
4.2	Discretized Blade model	35
4.3	Model of the blade 1 <sup>st</sup> Mode	38
4.4	Model of the blade 2 <sup>nd</sup> Mode	38
4.5	Model of the blade 3 <sup>rd</sup> Mode	39
4.6	Model of the blade 4 <sup>th</sup> Mode	39
4.7	Model of the blade 5 <sup>th</sup> Mode	40
4.8	Normal blade natural frequency spectrum	40
4.9	Aeroelastic model of the blade	41
4.10	Experimental and computational vibrational amplitude for the normal blade at rotor speed of 300 rpm	48
4.11	Experimental and computational vibrational amplitude for the normal blade at rotor speed of 600 rpm	49
4.12	Experimental and computational vibrational amplitude for the normal blade at rotor speed of 900 rpm	49
4.13	Experimental and computational vibrational amplitude of the normal blade at rotor speed of 1200 rpm	50
4.14	Experimental and computational vibrational amplitude for the normal blade at rotor speed of 1500 rpm	50
4.15	CFD simulation of the velocity flow inside the working section, inlet velocity is 8 m/s	51
4.16	CFD simulation of the pressure inside the working section,	

	inlet velocity is 8 m/s	52
4.17	Blade/vane configuration	52
4.18	Velocity and pressure modeling for the aligned configuration	52
5.1	Photograph of the Bladed Disk	56
5.2	Photograph of the Inlet Guide Vane Assembly	57
5.3	Photograph of the Axial Fan	58
5.4	Photograph of the Honeycomb	59
5.5	Photograph of the Screen	59
5.6	Photograph of the flexible joint	60
5.7	Test Rig Layout	60
5.8	Test Rig photograph	61
5.9	Natural Frequency spectrum for Bearing A	62
5.10	Natural Frequency spectrum for Bearing B	63
5.11	Natural Frequency spectrum for the working section	63
5.12	Forced Frequency spectrum for working section against the rotor running speed (1500 rpm). Top: Blade response, Middle: Working section (Horizontal) and Bottom: Working section (Vertical)	64
5.13	Different angular locations of the blades	66
5.14	blade frequency response at 500 rpm and 0°	66
5.15	Blade frequency response at 500 rpm and 90°	67
5.16	Blade frequency response at 500 rpm and 135°	67
5.17	Blade frequency response at 500 rpm and at 180°	67
5.18	Blade frequency response at 500 rpm and at 270°	68
5.19	Blade frequency response at 1000 rpm and at 0°	68
5.20	Blade frequency response at 1000 rpm and at 90°	68
5.21	Blade frequency response at 1000 rpm and at 135°	69
5.22	Blade frequency response at 1000 rpm and at 180°	69
5.23	Blade frequency response at 1000 rpm and at 270°	69
6.1	Photograph of the Kistler Ceramic Accelerometer	72
6.2	Kulite Pressure Transducer	73
6.3	Slip Ring rotor segment and Brush Block	74
6.4	IMC C1 Data Acquisition Box	75
7.1	Photograph of the accelerometer attached to the blade	77

7.2	Photograph of the pressure transducer attached to the blade	77
8.1	Recommended Pitot tube locations for traversing round Ducts and square (quality assured to ISO 9001)	86
8.2	Traverse Locations	87
8.3	Distribution of flow velocity around the duct at different depths	89
8.4	Distribution of static pressure around the duct at different depths	89
8.5	Distribution of static pressure in the duct at different depths and fan speed of 900 rpm	90
8.6	Distribution of static pressure in the duct at different depths and fan speed of 1200 rpm	90
8.7	Distribution of static pressure in the duct at different depths and fan speed of 1500 rpm	91
8.8	Distribution of static pressure in the duct at different depths and fan speed of 2100 rpm	91
8.9	Distribution of static pressure in the duct at different depths and fan speed of 2400 rpm	92
8.10	Distribution of static pressure in the duct at different depths and fan speed of 2400 rpm	92
9.1	Natural frequencies (1st mode) variations for the normal twelve blades	94
9.2	Natural frequencies (2nd mode) variations for the normal twelve blades	95
9.3	Natural frequencies (3rd mode) variations for the normal twelve blades	95
9.4	Measured natural Frequency of the blade of length 148 mm	97
9.5	Measured natural Frequency of the blade of length 150 mm	98
9.6	Measured natural Frequency of the blade of length 153 mm	98
9.7	Measured natural Frequency of the blade of length 157 mm	99
9.8	Normal blade at different angular positions	103
9.9	Blade frequency responses at 500 rpm and 0°	104
9.10	Blade frequency responses at 500 rpm and 90°	104
9.11	Blade frequency responses at 500 rpm and 135°	105

9.12	Blade frequency responses at 500 rpm and 180°	105
9.13	Blade frequency responses at 500 rpm and 270°	106
9.14	Blade frequency responses at 1000 rpm and 0°	106
9.15	Blade frequency responses at 1000 rpm and 90°	107
9.16	Blade frequency responses at 1000 rpm and 135°	107
9.17	Blade frequency responses at 1000 rpm and 180°	108
9.18	Blade frequency responses at 1000 rpm and 270°	108
9.19	1 <sup>st</sup> mode frequency responses for different blades lengths when no airflow	110
9.20	1 <sup>st</sup> mode frequency responses for different blades lengths for airflow at 11.6 m/s	111
9.21	1 <sup>st</sup> mode frequency responses for different blades lengths for airflow at 13.54 m/s	112
9.22	1 <sup>st</sup> mode frequency responses for different blades lengths for airflow at 15.67 m/s	
9.23	1 <sup>st</sup> mode frequency responses for different blades lengths for airflow at 17.58 m/s	113
9.24	1 <sup>st</sup> mode frequency responses for different blades lengths for airflow at 19.7 m/s	114
9.25	2nd t mode frequency responses for different blades lengths when no airflow	116
9.26	2nd t mode frequency responses for different blades lengths for airflow at 11.6 m/s	116
9.27	2nd t mode frequency responses for different blades lengths for airflow at 13.54 m/s	117
9.28	2nd t mode frequency responses for different blades lengths for airflow at 15.67 m/s	117
9.29	2nd t mode frequency responses for different blades lengths for airflow at 17.58 m/s	118
9.30	2nd t mode frequency responses for different blades lengths for airflow at 19.7 m/s	118
9.31	Overall frequency responses for different blades lengths when no airflow	120
9.32	Overall frequency responses for different blades lengths	



	for airflow at 11.6 m/s	120
9.33	Overall frequency responses for different blades lengths for airflow at 13.54 m/s	121
9.34	Overall frequency responses for different blades lengths for airflow at 15.67 m/s	122
9.35	Overall frequency responses for different blades lengths for airflow at 17.58 m/s	123
9.36	Overall frequency responses for different blades lengths for airflow at 19.7 m/s	123
10.1	Pressure responses on the vane surface of 148 mm blade at different rotor speeds	129
10.2	Pressure responses on the blade surface of 148 mm blade at different rotor speeds	129
10.3	FFT spectrum of the acceleration and pressures on the vane and blade surfaces for the 148 mm blade when no airflow at 300 rpm	130
10.4	Pressures on the vane and blade surfaces for the 148 mm blade when no airflow at 300 rpm	130
10.5	FFT spectrum of the acceleration and pressures on the vane and blade surfaces for the 148 mm blade at 11 m/s and 300 rpm	131
10.6	Pressures on the vane and blade surfaces for the 148 mm blade at 11 m/s and 300 rpm	131
10.7	FFT spectrum of the acceleration and pressures on the vane and blade surfaces for the 148 mm blade at 13 m/s and 300 rpm	132
10.8	Pressures on the vane and blade surfaces for the 148 mm blade at 13 m/s and 300 rpm	132
10.9	FFT spectrum of the acceleration and pressures on the vane and blade surfaces for the 148 mm blade at 15 m/s and 300 rpm	133
10.10	Pressures on the vane and blade surfaces for the 148 mm blade at 15 m/s and 300 rpm	133
10.11	FFT spectrum of the acceleration and pressures on the vane	

	and blade surfaces for the 148 mm blade at 17 m/s and 300 rpm	134
10.12	Pressures on the vane and blade surfaces for the 148 mm blade at 17 m/s and 300 rpm	134
10.13	FFT spectrum of the acceleration and pressures on the vane and blade surfaces for the 148 mm blade at 19 m/s and 300 rpm	135
10.14	Pressures on the vane and blade surfaces for the 148 mm blade at 19 m/s and 300 rpm	135
10.15	FFT responses for the blade acceleration and the pressure on the blades and vane surfaces for 148 mm and 300 rpm	136
10.16	FFT responses for the blade acceleration and the pressure on the blades and vane surfaces at 11 m/s and 900 rpm	136
10.17	FFT responses for the blade acceleration and the pressure on the blades and vane surfaces at 11 m/s and 1200 rpm	137
10.18	FFT responses for the blade acceleration and the pressure on the blades and vane surfaces at 11 m/s and 1500 rpm	137
10.19	FFT responses for the blade acceleration and the pressure on the blades and vane surfaces at 1300 rpm and 19 m/s and length 148 mm	138
10.20	FFT responses for the blade acceleration and the pressure on the blade and vane surfaces at 1300 rpm, 19 m/s and length 150 mm	138
10.21	FFT responses for the blade acceleration and the pressure on the blades and vane surfaces at 1300 rpm, 19 m/s and length 153 mm	139
10.22	FFT responses for the blade acceleration and the pressure on the blades and vane surfaces at 1300 rpm, 19 m/s and length 157 mm	139
11.1	Blade frequency response for no airflow and nominal stagger angle 25°	145
11.2	Blade frequency responses for normal and distorted flow at 12.23 m/s	145
11.3	Blade frequency responses for normal and distorted flow	

	at 14.42 m/s	146
11.4	Blade frequency responses for normal and distorted flow at 16.12 m/s	146
11.5	Blade frequency responses for normal and distorted flow at 18.41 m/s	147
11.6	Frequency responses for normal flow at different airflow	147
11.7	Frequency responses for distorted flow at different Airflow	148
11.8	Blade response at 18.41 m/s, stagger angle 25° and 1500 rpm	148
11.9	Blade response at 18.41 m/s, stagger angle 15° and 1500 rpm	149

## LIST OF SYMBOLS

$A$	-	Area
$C_L$	-	Lift coefficient
$E$	-	Modulus of elasticity
$e$	-	Distance from aerodynamic center to elastic axis.
$f$	-	Natural frequency
$I$	-	Moment of inertia
$K$	-	Stiffness
$K_n$	-	Translation spring stiffness
$L$	-	Lift or vertical force
$l$	-	Length
$M_{AC}$	-	Moment about aerodynamic center
$M$	-	Mass
$N$	-	Rotational Speed
$RPM$	-	Revolution per minute
$S$	-	Blade surface area
$q$	-	Dynamic pressure
$U_\infty$	-	Flow velocity
$\Lambda$	-	Effective structural damping
$\alpha$	-	Angle of attack
$\rho$	-	Density
$\omega$	-	Natural Frequency
$\omega_o$	-	Natural frequency with no rotation
$\omega_{Aero}$	-	Aerodynamic excitation frequency
$\xi$	-	Damping Coefficient
$\xi_{aero}$	-	Aerodynamic damping ratio
$\xi_S$	-	Structural damping constant

$\psi$	-	Total effective damping
$F_{Aero}$	-	Aerodynamic excitation force
$\lambda_1$	-	Stagger angle of the vane
$\lambda_2$	-	Stagger angle of the blade
$\Phi$	-	Phase angle
$Q$	-	Volume of Airflow
$P_t$	-	Total pressure
$P_s$	-	Static pressure

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 INTRODUCTION**

The study of blade dynamics in turbomachinery is an important area as blade failures represent the most common failure in gas and steam turbines. Blades can potentially suffer from failures (structurally and thermally) as they operate under elevated temperature and high forcing conditions. Dynamics of most engineering structures are usually studied experimentally by identifying the natural frequencies and mode shapes of the structure. Severe vibratory loads on the blades may cause cracks and ultimately blade failure. This in many cases leads to the total failure of the engine. During the development phase, such events cause delays and extra costs; with production engines, risks to passengers and the manufacturer's reputation result additionally.

Mode shapes are quantified from modal analysis which considers measured acceleration, velocity, or displacement of selected locations on the structure. Periodic structures, such as bladed disks, are however more difficult to analyze using modal analysis software due to the characteristic high modal densities. Therefore, the mode shapes and the natural frequencies of the bladed disk are measured by examining the forced responses of the structure to single blade excitations.

Blade Modal Analysis provides a mean to define the vibratory motion for each blade natural frequency. This illustration is useful for redesign of blade sets to

avoid resonances. For example, the shrouds and lashing are features that can be readily adjusted for grouped blade sets to affect their natural frequencies. Modal analysis requires that a number of vibration points be recorded for each test to clearly define the details of motion. The required mass and stiffness changes to tune natural frequencies can be estimated with acceptable accuracy.

## **1.2 FACTORS AFFECTING BLADE VIBRATIONS**

Most components in a gas turbine engine are exposed to vibrations caused by unsteady forces due to relative motions of rotating and non-rotating parts. Among the rotating parts are the blades. Many mechanisms are defined describing the vibrations of turbomachinery blades, usually classified according to the origin of excitation. These can be mechanical, thermal or aerodynamic nature. Mechanical excitations include blade tip casing contact or foreign object damage; aerodynamic excitations include blade row interaction, self excitation, impact of cooling jets, compressor surge and rotating stall as well as turbulence.

The steady load of the blade, which is the steady aerodynamic load and the centrifugal force in rotating parts, causes a static displacement and the steady stress whereas the unsteady load can lead to blade vibrations and thereby cause the alternating stress.

### **1.2.1 SELF EXCITED VIBRATIONS**

When the vibrations are self excited (flutter) the vibration motion of the blade itself causes an unsteady pressure field around the blade sustaining the vibration. Such behavior is usually started by small aerodynamic or mechanical disturbances above a critical flow speed. It can lead to drastically increasing blade vibration amplitudes and rapid blade failure, if the mechanical damping is too low to dissipate the aerodynamic energy put on the blade. Long and slender structures are more prone

to flutter, i.e. the fan blades and 1<sup>st</sup> stage compressor blades, but also low pressure turbine blades. Flutter is not a problem in the high pressure turbine.

### **1.2.2 FORCED VIBRATIONS**

Forced vibrations (forced response) are characterized by aerodynamic excitation sources, which are flow disturbances acting periodically on the blades and originate from upstream and/or downstream obstacles. The most common forced vibrations are due to inlet distortions originating at the air intake (inlet struts, cross winds), blade row interactions and hot streaks originating from the burners. Also the burner cans themselves cause circumferential variations in the burner exit flow. The time-periodic excitation is in all cases caused by the relative rotational motion of excitation source and the excited structure, which leads to excitation frequencies multiples of the rotation frequency. A common way to illustrate forced response regions of a blade row is the “Campbell Diagram”.

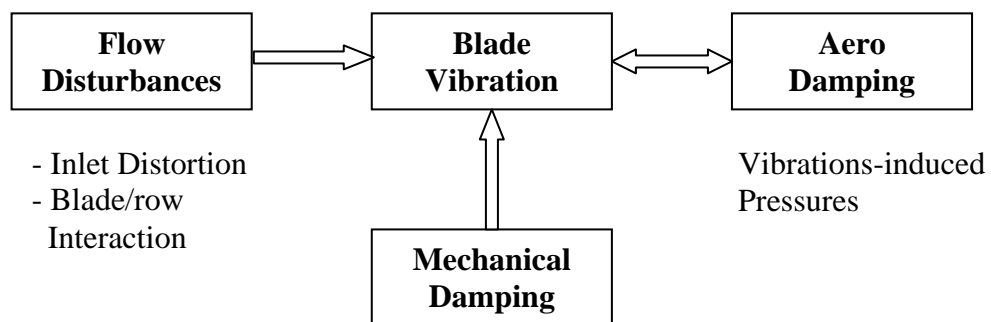
### **1.2.3 AERODYNAMIC EXCITATIONS OF TURBOMACHINERY BLADES**

If turbomachinery blades are aerodynamically excited to vibrate, no matter if self- or externally excited, a complex interaction between the unsteady flow around the blades and the involved solid structures takes place: The unsteady flow causes the blades to vibrate, whereas the blade motion itself modifies the unsteady flow. Hence, a coupling exists between the structural behavior of the blades (mass, stiffness, damping, friction, fixation) defining the blade motion and the unsteady flow defining the excitation. This is classically shown by “Collar’s Triangle of Forces” [Collar 1946], which illustrates the interaction between inertia forces, elastic forces and aerodynamic forces. This triangle is sometimes extended by a vertex for thermal forces and a vertex for control forces, two additional parameters increasing the complexity of the problem.



### 1.3 AEROELASTICITY OF TURBINE BLADE

Aeroelasticity deals with the science that studies the mutual interaction between aerodynamic forces and elastic forces. The parameters affecting side interaction is indicated in Fig. 1.1. The blade in the turbomachinery is subjected to surface pressures induced by the flow. If the incident flow is unsteady or the boundary conditions are time-dependent, these pressures become time-dependent. Moreover, if the structure undergoes dynamic motions, it changes the boundary conditions of the flow and the resulting fluid pressures, which in turn change the deflections of the structure. Flutter and buffeting are examples of such fluid-structure interaction.



**Figure 1.1** Fluid-structure interactions

In order to predict the dynamic response of a rigid or flexible structure in a fluid flow, the equations of motion of the structure and the fluid must be solved simultaneously. The most difficult part in handling numerically the fluid/structure coupling stems from the fact that the structural equations are usually formulated with material (Lagrangian) co-ordinates, while the fluid equations are typically written using spatial (Eulerian) co-ordinates. Straightforward approach to the solution of the coupled fluid/structure dynamic equations requires moving at each time step at least the portion of the fluid grid that are close to the moving structure. This can be appropriate for small displacements of the structure but may lead to severe grid distortions when the structure undergoes large motion.

Forced response analysis involves modeling the interaction between the unsteady flow around the blade and the motion of the blade structure. Blade vibration

is caused by the unsteady flow through the machine from upstream disturbances such as non-uniform inlet flow (inlet distortion) or upstream blade wakes (blade row interaction). However, vibration of the blade structure induces an unsteady pressure field around the blade causing energy dissipation, resulting in aerodynamic damping.

## **1.4 MISTUNING**

The design of turbomachine blades is rendered particularly challenging by a series of factors such as the inherent structure-fluid interaction problem, mistuning, the effects of rotation, temperature, etc. Noteworthy in this list is mistuning, i.e. the presence of small blade-to-blade variations of their structural and/or geometrical properties, which may produce large increases in the forced response of some of the blades. Since these differences originate for example from finite manufacturing tolerances, in-service wear, foreign object damage, they cannot be precisely quantified and thus are often modeled as random variables. While mathematically convenient, this representation implies the need to solve a particularly difficult random vibration problem, e.g. the estimation of the statistics of the largest responding blade on the population of mistuned disk, to determine the expected fatigue life of the corresponding bladed disks.

Mistuning in bladed disks can result in blade forced response amplitudes and stresses that are much larger than those predicted for a perfectly tuned assembly. Thus, mistuning has a critical impact on high cycle fatigue (HCF) in turbine engines, and it is of great importance to be able to predict the mistuned forced response in an accurate and efficient manner.

## **1.5 INLET FLOW DISTORTION**

Total pressure distortions occur in gas turbine engines when the incoming airflow is partially blocked or disturbed. Distorted inlet conditions can have varying

effects on engine performance and engine life. Short-term effects are often in the form of performance degradation where the distorted airflow causes a loss in pressure rise and a reduction in mass flow and stall margin. Long-term effects are a result of vibratory blade response that can ultimately lead to high cycle fatigue (HCF), which in turn can quickly cause partial damage to a single blade or complete destruction of an entire compressor blade row, leading to catastrophic failure of the gas turbine engine. A better understanding and prediction of vibratory blade response is critical to extending engine life and reducing high cycle fatigue induced engine failures.

The immediate effects of distortions often related to the degradation in the performance of the engine and reduction in fan and compressor stall margin. Long-term effects produce periodic unsteady flows on rotating blades, and are implicated in HCF failures. The unsteady loading on the blades can pose a serious problem if frequencies contained in the periodic distortion waveform and natural frequencies of the blade coincide, which can lead to rapid blade failure. High cycle fatigue (HCF) is observed as metal fatigue due to stress cycles at a sufficient level and duration to produce fatigue failure. For turbomachines this can occur relatively quickly, considering the high rotational speeds.

The occurrence of fatigue-producing stress levels with realistic levels of inlet flow distortions will be associated with resonant response of a blade or blade system. Thus, HCF problems associated with flow distortions will typically be associated with coincidence of periodic frequency content of the distortion waveform with a frequency of modal response of the rotating blades. It is believed that the dominant driver of non-uniform flow-related HCF is total pressure flow profile distortions. Distorted total pressure profiles such as those obtained from distortion screen tests can be applied as input to mathematical models relating the periodic input total pressure distortion to the dynamic response of the blade and HCF potential.

## 1.6 VIBRATORY STRESSES PREDICTION

The prediction of the vibratory stress level for input to the stress-range diagram requires the analysis of the blade row unsteady aerodynamics, structural characteristics, and resonant vibration response. This is because the root cause of the vibratory stress is flow induced vibrations. Namely, integral order forced vibrations can occur in fan, compressor, and turbine blading when a periodic aerodynamic forcing function, with frequency near a system resonant frequency acts on a given blade row. These forcing functions are generated at multiples of the engine rotational frequency and arise from a variety of sources both internal and external to the engine.

The rotor speeds at which significant forced vibrations may occur are predicted with frequency-speed or Campbell diagrams. To predict blade life or design blades for longer HCF life, accurate predictions of the blade vibratory stress are crucial. First the airfoil row is designed to achieve its steady performance requirements. Based on this design, the blade natural frequencies and mode shapes are analyzed by means of a finite element structural analysis; with the detailed blade row steady aerodynamics predicted utilizing a computational fluid dynamics (CFD) model.

The blade row unsteady aerodynamics are then predicted utilizing CFD analysis to predict the aerodynamic damping together with the aerodynamic forcing functions and the resulting gust response. Current design system unsteady aerodynamic analyses generally consider the response of an isolated blade row, with both linear frequency domain and nonlinear time-marching analyses utilized. Both approaches require the specification of the unsteady aerodynamic forcing function and the vibration mode shape. Thus, there are two separate systems of equations to be solved – the structural system and the fluid system. They are coupled only in that aerodynamic forces and blade state are passed between each other after each time step.

The structural characteristics of the blading, including the mode shapes and natural frequencies, are predicted with finite element analyses. The structural analysis is then coupled with the unsteady aerodynamic analysis through an

aeroelastic forced response analysis that predicts the airfoil vibration response. A separate analysis is then required to determine the resulting vibratory stress. The potential for HCF failure is then predicted by determining the effect of the combined mean and cyclic stress, accomplished with stress-life (S-N) diagrams which are concerned with component life to failure.

## **1.7 FATIGUE LIFE PREDICTION OF TURBOMACHINE BLADING**

HCF of turbomachinery blading is a significant design problem because fatigue failures can result from resonant vibratory stresses sustained over a relatively short time. Fatigue failure may result from a combination of steady stress, vibratory stress, and material imperfections. However, the size of microscopic imperfections is difficult to control. Hence, stress-range diagrams are used to quantify the allowable vibratory stress amplitudes to avoid fatigue damage. Advanced turbomachinery blading is designed to have high steady stress levels. Thus, HCF occurs because of high mean stress - low amplitude vibratory loading of the airfoils. The prediction of the vibratory stress level for input to the stress-range diagram requires the analysis of the blade row unsteady aerodynamics, structural characteristics, and resonant vibration response. This is because the root cause of the vibratory stress is flow induced vibrations.

In summary, high cycle fatigue (HCF) of turbomachinery blading is a significant design problem because fatigue failures can result from resonant vibratory stresses sustained over a relatively short time. Blade and thus engine durability and life are dependent on the vibratory stress level for a given steady operating stress. To avoid costly and time consuming development problems and to maximize engine life and time between overhauls, it is necessary to accurately predict the level of vibratory stress. This requires the analysis of both the structural mechanics and the unsteady aerodynamics of bladed disks to predict the vibratory stress level, with a stress range diagrams utilized to predict the maximum vibratory stress for infinite life.

## 1.8 FLOW DEFECTS

In case of forced response blade vibrations the aerodynamic excitation mechanism is due to flow defects, which are spatial non-uniformities in the flow field upstream or downstream of the observed blade row. These flow defects are usually regarded as steady in the reference frame of the generating obstacles. They become unsteady when moving relative to the observed blade row. Flow defects can be related to different physical phenomena, the most relevant are listed below:

- Wakes are generated due to the development of a boundary layer on the blade surfaces, which separate from the blade at its trailing edge. The wakes are characterized by a velocity deficit of a certain magnitude, a spatial width and a (negligible) small static pressure deficit. The low momentum fluid inside the wake has increased vorticity and entropy and is convected with the local flow velocity. It is clear that the wake is a completely viscous phenomenon. Many empirical and semi-empirical models exist to describe the wakes behind turbomachine blades.
- Vortex shedding behind a vane or blade is another flow defect related to the detachment of the boundary layer at the trailing edge. In case of occurrence left and right rotating vortices are shed at a Reynolds number dependent frequency, which is usually much higher than typical wake passing frequencies. The related disturbance on the downstream rotor is hence a superposition of wake passing and vortex shedding. Due to the high frequency and small velocity variations the vortex shedding related excitation is usually not regarded in forced response problems. However, it has a significant impact on performance.
- The static pressure field upstream and downstream of a blade row is varying circumferentially (and radially) due to the blade load. This causes a flow defect, which is felt as unsteady pressure waves by the relative moving blade rows.

- Shock waves are a special category of pressure waves, which occur due to the strong pressure gradient over a shock. This gradient is experienced as unsteady pressure wave by relative moving blades. The shock excitation in transonic turbine stages is probably the main contributor to blade vibration excitations.

It is obvious that the control of the flow defect has the potential to control the blade excitation and hence the blade vibration. In particular, the various flow defects can interact with each other (i.e. wakes and pressure waves, shock – wake interaction) and by that either amplify or diminish blade excitation.

The idea of non-uniform inlet conditions leading reduced compressor performance is not new and has been the subject of many experimental and analytical studies dating back to 1950s. All of these works have concentrated on the reduction of compressor performance in the form of reduced stall margins and pressure rise. The present work is aimed at identifying the influence of flow defect (unsteady aerodynamic loading on the blade surface) and its interaction on vibrational frequency responses of the blade excitation.

## **1.9 PROBLEM DEFINITION**

Gas and steam turbines are considered the main driving elements for the power plants. Moreover, gas turbines are used in airplanes engines. Being important and critical machinery, their performance, reliability and efficiency should be monitored and controlled as close as possible. Turbine engines blades (compressor or turbine) are the most critical component in the turbine, because they are responsible for extracting the kinetic energy in the flow and convert it into mechanical energy. Blades operate in a severe environment, and are subjected to elevated temperature and high stresses for a very long operation period (minimum period for overhaul is averaged to 3 years). In addition, the maintenance cost for turbine is usually very high, especially when it is concern with blades, because to inspect or repair the blade needs the plant to shutdown for few days or longer. The problems in industrial

turbines can be classified into three categories according to work done with respect to:

- 1- Problems which were well understood and solved. Examples are the resonance, surge and stall problems.
- 2- Problems that are solved partially, these are problems that associated with the materials used for manufacturing turbines components.
- 3- Problems that are not fully understood and still a lot of researches are on going. These are the aeromechanical and aerodynamic behavior of the blades.

One of the main problems that encountered when dealing with blade is that some blades are subjected to higher stresses than the others. The higher vibratory stresses are responsible for failure due to high cycle fatigue (HCF). Previous researchers showed that these blades (failed ones) were slightly differing from the other blades due to manufacturing tolerance or wear as a result of operation. They named this phenomenon as blade mistuning.

Other common problem associated with blade is the non-uniform aerodynamic loading. The non-uniformity arises from many causes mainly from the non-uniform fuel burning due to some defective burners (defective burners supply more fuel). This non-uniform aerodynamic loading on the blade leads to severe stress fluctuation and hence to blade High Cycle Fatigue (HCF).

## **1.10 PROBLEM FORMULATION**

This work involved studies of blade mistuning by simulating a nearly realistic environment involving rotating blades in the presence of airflow, i.e. the interaction of structural and aerodynamic and their impact on mistuning. The primary intent was to acquire the data while the blade is rotating as a simulation of the actual industrial situation. Previous work by others usually involved a non-rotating blade. This work therefore involved the experimental study of forced response amplitude of model blades due to structural mistuning in the presence of airflow. The work



included the study of forced response amplitudes of the flow distortion (non-uniform aerodynamic loading) arising from changing the inlet vane angle. To achieve this goal the study investigated this situation but there were still a number of questions that could be raised with the respect to bladed disk vibration and force response with the interaction of airflow.

This work attempted to address the following questions:

- 1- What are the real responses of blade mistuning when the data is taken from a rotating blade?
- 2- What are the additional effects that the airflow and the stagger angle will add to the blades vibrational responses?
- 3- What is the effect of changing the inlet vane angle on the blade vibrational responses?

The work was intended to:

- 1- Demonstrate the change in forced response amplitude due to mistuning.
- 2- Investigate the impact of the airflow excitation and the stagger angle on the sensitivity of forced response amplitude to mistuning.
- 3- The validity of acquiring data from a rotating blade.

In order to address the problems above, the study aims to undertake a thorough analysis of bladed disk vibration from both theoretical and experimental aspects.

## **1.11 SIGNIFICANCE OF THE PROBLEMS**

Vibration induced fatigue has always been one of the main concerns to turbomachinery blading and hence the theoretical prediction of the natural frequencies, mode shapes and forced response level is of vital importance for designing away from the ranges where the stresses are likely to be high. Vibrations problems in turbomachinaries are of two types, globally and locally-occurring vibrations. The first type involved the motion of the whole structure while the second

type was restricted to a few internal components such as discs, blades and shroud attachments. Failures due to problems of the first kind are usually related to bearing and/or shafts and their study is outside the scope of this work which focused on the bladed disk vibration in the presence of air flow.

The inevitable occurrence of blade mistuning in turbomachinery rotors is known to cause vibration localization among the blades. This in turn increases the likelihood of an excessive vibration response at certain conditions, thus posing a major safety concern. This problem motivates the exploration of the various factors that affect the degree to which the response of a bladed disk increases as a result of mistuning. Moreover, mistuning is known to dramatically impact the stability and forced response of the bladed disks found in turbomachinery. In addition, mistuning in bladed disks can result in blade forced response amplitudes and stresses that are much larger than those which would be predicted for a perfectly tuned assembly. Thus mistuning has a critical impact on the high cycle fatigue in turbine engines, and it is of great importance to be able to predict the mistuned forced response in an accurate and efficient manner.

The motivation for considering such small variations is that their effects on the forced response of the bladed disks can be extremely large, i.e., fluctuations of the blade properties by 1 to 2% can lead to increases of the amplitude of vibration of some blades by 100% or more. These results were obtained theoretically and experiments were done to validate them, so the proposed work studied the effect of aerodynamic damping, structural mistuning and stagger angle in the frequency shift which will give a clear understanding to the value of the force response from the mistuning and hence nearly realistic effects can be predicted.

On the other hand, the inlet flow distortion in the as mentioned above, the previous studies concentrated on the airflow distortion on the compressor as happened in the practical life when the military fighter suddenly changes its direction during maneuvering. In this study the airflow distortion in the turbine side was studied. In the turbine the unsteady aerodynamic loading takes place when the blades are subjected to non-uniform aerodynamic loading. This non-uniform aerodynamic loading on the blades can arise in the real life when the inlet flow to turbine is

distorted by a deflected vane. Moreover, malfunctioning of some burners, improper combustion of the gases in some chambers alter the uniformity and symmetry of the aerodynamic loading on the blades surfaces.

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